



# Sustainable waste management through synergistic utilisation of commercial and domestic organic waste for efficient resource recovery and valorisation in the UK

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## ABSTRACT

The UK is facing tremendous challenges in tackling food waste diversion from landfill. Whilst much effort has been made to prevent food waste, there is still a lack of attention and strategic approach in dealing with resource recovery and valorisation of food waste. This paper presents a systematic framework for sustainable organic waste management and valorisation in the UK through (i) review of current policy framework; (ii) analysis of resource recovery potential from food waste at national, community and organisational levels; (iii) proposition of alternative waste management strategies; and (iv) examination of challenges and opportunities with respect to economic, environment and social dimensions of sustainability of waste management strategies. The paper explores valorisation of source-segregated food waste and mixed waste from the supermarket and households into electricity and transportation fuels, through partially and completely decentralised configurations using anaerobic digestion and gasification technologies. This study demonstrates a potential for reducing the cost of electricity and greenhouse gas emissions of one supermarket store by 12% when adopting partially decentralised food waste anaerobic digestion strategy, and full substitution of fossil fuel based electricity with net surplus renewable electricity generation through complete decentralisation of mixed waste gasification. Therefore, a more integrated, circular and advanced technological approach in waste management should be undertaken as it can lead to a wider range of socio-economic and environmental advantages to the local community, highly essential in the UK.

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## 1. Introduction

Food waste is urgently needed to be reduced and diverted from the landfill, as advocated by *The UK's Clean Growth Strategy* (HM Government, 2017), *Resources and Waste Strategy for England* (HM Government, 2018), *the Roadmap to a Resource Efficient Europe* (COM/2011/0571) (European Commission, 2011) and the United Nations Sustainable Development Goals (SDG) 12.3 (United Nations, 2015). At present, the UK policy suggests a socially-oriented voluntary approach to waste management, through prevention of food surplus which is safe for human consumption (e.g. education, relabelling “best before” and “use by” dates on food, redistribution to charities), whilst paying limited attention to

recovery of valuable resources from food waste. Conventional approach to dealing with food waste in the UK includes composting, energy recovery through anaerobic digestion (AD) and incineration. These practices are widely adopted in the UK mainly due to government support (e.g. subsidies) offered to these technologies. However, these technologies have limited the potential for utilisation of resources embedded in food waste. Most of the policy discussions are focusing on household food waste while food waste from commercial organisations are often overlooked (European Parliament, 2017). In the present context, supermarkets, i.e. large, out-of-town stores with own land, can play a key role in improving the efficiency of waste management processes at local community level through monitoring and controlling food purchase and supply as well as food surplus and waste (Schanes et al., 2018). A significant amount of food waste is concentrated at the supermarket which can be exploited conveniently to produce value-added products such as transportation fuel and electricity and can be

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distributed to the local community. In view of achieving a more sustainable resource management and maximum environmental and socio-economic benefits, it is highly recommended to transform the current waste management approaches from a linear “take-make-dispose” model to a circular economy model (Ellen MacArthur Foundation, 2014; European Parliament, 2017; HM Government, 2018) where waste becomes a resource to another value-added production process. Concerted efforts in research and innovation are needed at all levels (e.g. social, technological and commercial) to realise a feasible circular economy in waste management and thereby enhance resource efficiency (Stahel, 2016).

Food waste problem should be addressed at a system level through multi-stakeholder collaboration and interactions between various business and industrial sectors (Halloran et al., 2014; European Parliament, 2017). A community-based approach in waste management (Muller and Hoffman, 2001) is practised in developing countries due to limited governance of local authorities in managing the solid waste problems in rural areas. This approach can be adopted in the UK by enhancing participation of domestic, commercial and waste management sectors. Nevertheless, the impacts and benefits of adopting such a collaborative, decentralised approach in waste management in the UK and the effectiveness of utilising food or mixed waste from the local community into value-added production have not been well studied. Therefore, further research is needed to address these knowledge gaps and to develop an alternative strategy for future waste management in the UK.

This research aims to explore the potential of recovering and valorising source-segregated food waste and mixed waste from the commercial (i.e. supermarket) and domestic (i.e. households) sectors into electricity and transportation fuel production, and how circular economy thinking can be incorporated in waste management strategy in supermarkets and their adjacent communities through synergistic utilisation of resources, i.e. an integrated and collaborative approach. This paper presents a new framework for dealing with organic waste using a synergistic approach coined Systems Thinking Approach to Resource Recovery (STARR), and demonstrates its application using a case study of the UK. The proposed STARR framework comprises review of waste management policies at national level; followed by strategising waste management and valorisation through multilevel system analysis, scenario creation and sustainability assessment; and providing recommendations. The framework has been applied on the food waste management scenarios in the UK.

Section 2 examines the challenges of the existing waste management approaches and practices by reviewing current national policies. Section 3 outlines the methodology for design and analysis of alternative waste management strategies. Section 4 details the recovery and valorisation of food and mixed waste using a case study of the UK. Finally, the paper draws conclusions and recommendations in Section 5.

## 2. Review of food waste management approaches

### 2.1. Sustainability of food waste management

Centralised waste processing, where waste is collected from discrete sources and transported to a large-scale processing facility has been a preferred method in almost every country including the UK, where economies of scale and transport cost are the main drivers (Gorecki et al., 2010). Alternatively, decentralising the waste processing facility by locating it closer to the source of waste generation can be adopted, and this strategy may bring certain economic, environmental and social benefits (Righi et al., 2013; Pleissner, 2016; Venus et al., 2018). There is a pressing need to move towards a more advanced technological approach in valorising food

waste into higher value applications such as fuels and chemicals via biorefinery technologies (Lin et al., 2013; Luque and Clark, 2013; Sadhukhan et al., 2014). Much research has been ongoing on food waste valorisation into chemicals including succinic acid (Patsalou et al., 2017) and lactic acid (Venus et al., 2018); biofuels such as biodiesel and bioethanol (Karmee and Lin, 2014); and biopolymers such as plastics (Nisticò et al., 2017). Commercialising these valorisation technologies in the UK is still challenging due to the lack of government support whereas the economic viability of implementing these technologies has not yet been guaranteed.

Various frameworks are offered in the literature which are particularly useful for high-level strategy assessment and planning. These include the Integrated Sustainable Waste Management (ISWM) framework developed by Van de Klundert and Anschutz (2001) that consists of three dimensions: stakeholders, waste system elements and sustainability aspects. A refined framework using a “two-triangle” representation proposed by Scheinberg et al. (2010) and Wilson et al. (2013), taking into account public health, environment, 3R (reduce, reuse, recycle) and the “soft” governance aspect including inclusivity of users and service providers, financial sustainability as well as sound institutions and proactive policies. A multi-dimensional evaluation approach for resource recovery from waste system was proposed by Iacovidou et al. (2017a; 2017b) to capture the “complex values” of the environmental, economic, social and technical benefits and impacts. A framework with greater focus on integrated system design and sustainability analysis, based on a combination of the circular economy (Ellen MacArthur Foundation, 2014), industrial ecology (Clift and Druckman, 2015) and design for sustainability/Hannover principles (William McDonough & Partners, 1992), is desirable for developing food waste management and valorisation strategies.

The core idea of circular economy concept (Ellen MacArthur Foundation, 2014) is to preserve the value of materials and products for a longer period of time by closing the loop of product life cycles. By doing this, input of virgin materials and energy can be minimised, or ideally be avoided, and hence the environmental burdens associated with resource extraction, production, consumption and disposal can be reduced (Iacovidou et al., 2017a; Cobo et al., 2018). Industrial ecology (Clift and Druckman, 2015) advocates for exploitation of interactions between industrial activities and ecological systems where waste and by-products from one activity become an input to another process. The exchange of materials and energy in the system can be quantified using material flow analysis (Brunner and Rechberger, 2004), which is an important tool for accounting stocks and flows within a defined system boundary. Design for sustainability or Hannover principles (William McDonough & Partners, 1992) emphasise the interdependence of economic and social development with nature as well as elimination of the concept of waste. The common grounds of all the above principles are to treat waste as resource and adopt a whole systems approach in designing resource supply. The systems should be explored using sustainability assessment (Santoyo-Castelazo and Azapagic, 2014), a holistic tool used for evaluating benefits and impacts of the system design by considering economic, environmental and social dimensions.

### 2.2. Current UK food waste management approach and policies

#### 2.2.1. Regulatory framework

Most of the food waste reduction initiatives in the UK are carried out on a voluntary basis (Priestley, 2016; Filimonau and Gherbin, 2017). The UK waste management policies are primarily influenced by the *EU Waste Framework Directive* (Directive 2008/98/EC) (European Commission, 2008). The UK exercises “polluter pays principle” (Article 14) and “extended producer responsibility”

(Article 8) in accordance with the *EU Waste Framework Directive* (Directive 2008/98/EC) (European Commission, 2008) where various stakeholders in the supply chain (e.g. food manufacturers, distributors and consumers) are responsible for food waste generated and associated disposal costs at respective stages. Under the Directive, the UK is required to meet a minimum 50% recycling target of household waste by 2020 (European Commission, 2008). In addition, it is also mandatory to meet the reduction targets of biodegradable municipal solid waste going to landfill of 75% by 2010, 50% by 2013 and 35% by 2020, compared to the 1995 baseline level, as set out in the *EU Landfill Directive* (Directive 1999/31/EC) (European Commission, 1999). The ultimate goal is to eliminate food waste disposal to landfill, recognising that landfilling is the least preferable option. The EU has officially adopted the Circular Economy package on 4<sup>th</sup> July 2018 where Member States including the UK are required to meet the mandatory recycling targets of municipal waste of 55% by 2025 and 65% by 2035 (European Parliament, 2018). In the context of food waste (as well as other types of biowaste), separate collection must be undertaken and reduction targets have been set at 30% by 2025 and 50% by 2030 (European Parliament, 2018).

Fig. 1 shows the food waste hierarchy adopted in the UK, built on the principles outlined in the *EU Waste Framework Directive* (Directive 2008/98/EC) (European Commission, 2008). This approach has been incorporated into the UK legal framework through the *Waste (England and Wales) Regulations 2011*, the *Waste Regulations (Northern Ireland) 2011*, and the *Waste (Scotland) Regulations 2012* (House of Commons, 2017). The food waste hierarchy suggests that prevention is the most preferable option for food surplus where raw materials, ingredients and products should be minimised wherever possible. The fraction of food surplus that is safe for consumption should then be redistributed to human or used as animal feed. Non-preventable food surplus which is not safe for consumption is considered as “food waste”. The current food waste management practices are primarily focusing on AD and composting (recycling); incineration with energy recovery (recovery); and least preferably, landfill or incineration without energy recovery (disposal). Although energy recovery from waste is currently preferred in the UK, it is timely to consider higher value product generation from waste through valorisation.

## 2.2.2. Waste management strategies and practices

The UK has not yet adopted a unified approach in food waste management across England, Scotland, Wales and Northern Ireland (Priestley, 2016). Although food waste management (including collection, processing and disposal) has been regulated in the UK, food waste reduction (e.g. donation or redistribution of food surplus) has been carried out on a voluntary basis (House of Commons, 2017). Resource recovery from food waste can be carried out more effectively if separate food waste collection service is provided. Despite separate food waste collection has been made mandatory in Scotland, while Wales and Northern Ireland have also shown significant improvement in achieving higher recycling rate of food waste, the situation in England has not been improved since the legislation has not been made mandatory and local authorities have different approaches to separate food waste collection. In fact, there are only less than half of the local authorities in England offering such service (Hogg et al., 2016). The main barriers to the uptake of separate food waste collection include the uncertainty of recovering the cost of food waste collection and insufficient funding to support the collection services (economic factors); and low participation rate of households, i.e. perception that “separating food waste for collection is unpleasant and smelly” or the “yuck” factor (social factors) (Brook Lyndhurst, 2010; Hogg et al., 2016). It is hence essential to revise and standardise the strategies for food waste management while improving the regulations to enforce effective separate food waste collection and reduction strategies to be undertaken at different levels, enabling the UK to move towards zero waste to landfill.

## 2.2.3. Government support schemes

The UK Government currently promotes food waste to be recycled through AD to produce biogas and digestate and hence diverting the waste from landfill (Priestley, 2016; House of Commons, 2017). AD has been claimed to be an environmentally sound option in the *Anaerobic Digestion Strategy and Action Plan* (DEFRA, 2011) and has been supported through various financial incentives including the Feed-in Tariff (FiT) and the Renewable Heat Incentive (RHI). FiT has been created to promote renewable electricity generation technologies including AD and the scheme supports capacity of installation for up to 5 MW, except for micro combined heat and power (micro-CHP) which is only 2 kW (Ofgem, 2016). RHI supports a wide range of renewable heat technologies

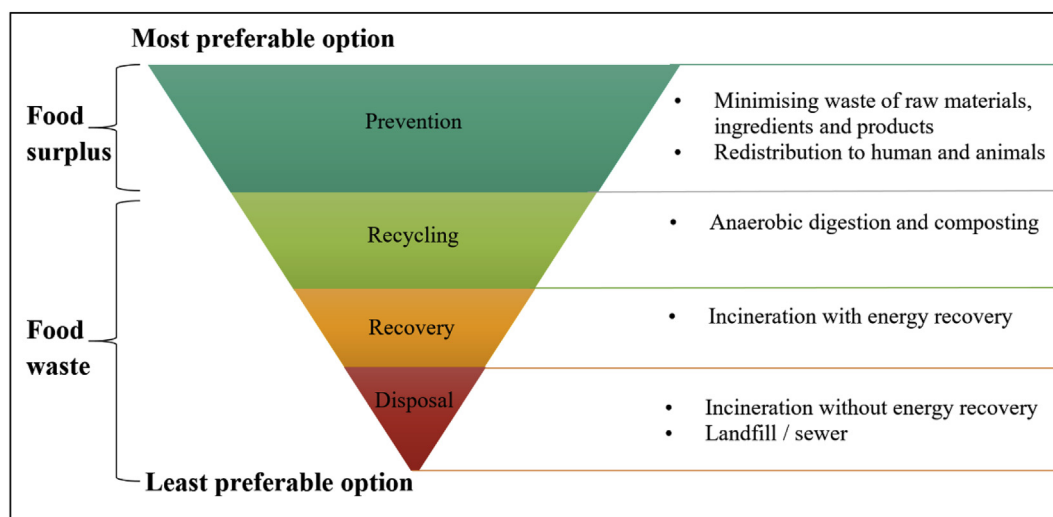


Fig. 1. Food waste management hierarchy adopted in the UK (WRAP, 2017a).

including solid biomass and biogas combustion (including CHP systems), biomethane injection and so on (Ofgem, 2018a). In addition to FiT and RHI, AD is also eligible for Contract for Difference (CfD) for a generating capacity above 5 MW (The Stationery Office, 2014). Apart from the support for renewable electricity, the UK is also offering incentives in the form of tradeable certificates – Road Transport Fuel Certificates (RTFC) for renewable fuel such as biomethane. RTFC is more relevant to the owners who supply fossil fuel based electricity and transportation fuel in a large scale generating facility (i.e. supplying over 450,000 L of fossil fuels) (Department for Transport, 2011). It can be seen that there are still rooms for improvement in the government support schemes to further promote technologies relevant to resource recovery from waste.

### 3. Methodology

The STARR framework, presented in Fig. 2, has been developed based on the principles of circular economy (Ellen MacArthur Foundation, 2014); industrial ecology (Clift and Druckman, 2015); and design for sustainability/Hannover principles (William McDonough & Partners, 1992). This study proposed three-stage analysis of the sustainable resource recovery and valorisation system (see Fig. 2): (1) multilevel system analysis; (2) scenario creation; and (3) sustainability assessment.

**Multilevel system analysis:** Material flow analysis (Brunner and Rechberger, 2004) using the multilevel system approach (Liu and Müller, 2013; Ng et al., 2016) has been carried out using Sankey diagrams to examine the flow of resources within the system boundary, from national level (i.e. country), through community level (i.e. households) to organisational level (i.e. supermarket). The main implications that can be derived from the material flow analysis are: (i) the availability of food waste from different sources can be used to determine the opportunity of resource utilisation

from different sectors (source analysis); and (ii) the flows of food waste to different treatment routes that determine the maximum resource recovery and valorisation potential (sink analysis). Multilevel system analysis was proposed by Liu and Müller (2013) and Ng et al. (2016) and demonstrated in their case studies for sustainable resource management (i.e. aluminium and zinc) to quantify resource flows at different levels. Multilevel system analysis enables systematic examination of the quantity (i.e. amount of food waste generation) and quality (i.e. nature of food waste generation) of the resources which gives reliable estimation for generating pragmatic scenarios and informing policy and decision-making at different levels. The sector which generates the highest resource flow at the national level has been selected for subsequent analysis since it possesses the greatest resource recovery potential. Synergistic utilisation of resources requires integration of two or more sectors and hence the analyses at community and organisational levels have been undertaken to examine the quantity and quality of resources that can potentially be utilised. The results from the multilevel system analysis have been used as the basis for formulating the relevant scenarios and have subsequently been employed in the sustainability assessment.

**Scenario creation:** Systematic formulation of scenario is an important step after multilevel evaluation of resource flows in view of identifying appropriate technological designs, location and resource utilisation strategies. The scenarios have been further examined and compared through sustainability assessment. Scenarios have been developed to explore business-as-usual systems as well as alternative systems by considering (i) configuration and (ii) technology of waste processing. For business-as-usual systems, centralised waste processing configuration using mature (existing) technologies has been adopted as the base case to compare against alternative systems. Alternative systems include decentralised configuration using existing or emerging waste processing technologies. In view of creating a resource efficient economy, the

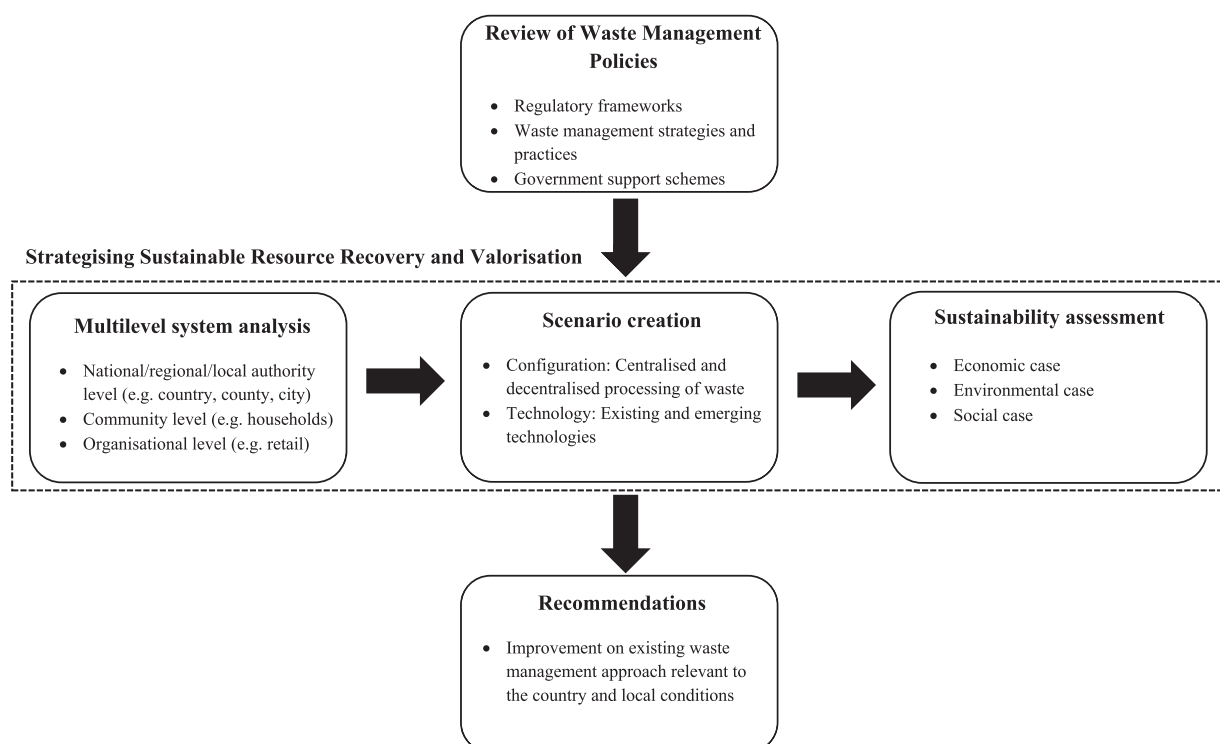


Fig. 2. Framework for Systems Thinking Approach to Resource Recovery (STARR).



development of scenarios must consider circular economy or “waste as a resource” strategy (Ellen MacArthur Foundation, 2014; European Parliament, 2017) and design for sustainability principles (William McDonough & Partners, 1992) that promote waste diversion from landfill (disposal practices) to recycling or reuse and recovery practices and hence reducing virgin resources consumption. A systems thinking design strategy with the consideration of economic, environmental and social aspects has been incorporated in the scenarios. In this study, the utilisation, recovery and valorisation of waste from the supermarket and households at a decentralised scale, together with their integration within the associated local community has been studied. In this context, energy recovery from waste and valorisation of waste into higher value products such as transportation fuel have been considered.

**Sustainability assessment:** The impacts and benefits of the scenarios have been examined through sustainability assessment which considers economic, environmental and social dimensions (Sadhukhan et al., 2014; Santoyo-Castelazo and Azapagic, 2014). This is a holistic assessment approach which takes into account integrated thinking of the system from different perspectives and it allows us to make sound decisions and assertions of what action should be taken in order to make the system more sustainable. Economic cost-benefit analysis examines the investment costs of the facility, value of product generated from waste valorisation, fiscal incentives and transportation cost of waste. Greenhouse gas (GHG) emission has been used as the indicator for the environmental impact assessment in the present context since it is widely adopted in environmental reporting (DEFRA, 2013) as specified in PAS 2050 (British Standards Institution, 2011) and GHG Protocol (World Resources Institute and World Business Council for Sustainable Development, 2004). For social dimension, public acceptance and participation with respect to social function and equity and level of involvement; health and safety and job creation have been explored (Santoyo-Castelazo and Azapagic, 2014; Iacovidou et al., 2017b).

#### Sources of data

**Multilevel system analysis:** The present study has adopted secondary data from WRAP and Tesco in conducting the multilevel system analysis. WRAP has published comprehensive food waste data at the national level (WRAP, 2017a) of which the data related to the amount of food waste in each stream has been adopted in the present study. This data has been estimated using various sources of raw data include *WasteDataFlow*, *Down the Drain* and *Kitchen Diary* (WRAP, 2013a). With respect to organisational level analysis, the availability of food waste from supermarkets that can potentially be recovered or valorised has been examined using the published data from Tesco (2017). Tesco has been studied because it is the largest grocery in the UK with market share of 19% (DEFRA, 2017) and the data is readily available, transparent and comprehensive, thus giving high confidence to the analysis. Tesco estimated the amount of food waste generated from their organisation based on a number of primary data sources, including retail waste, depot waste, product data, self-scan data, bakery weights data, Community Food Connection Donations and other charity data, colleague shop and animal feed tonnage (Tesco, 2018).

**Sustainability assessment:** The mass and energy balances information of the technical systems as well as the data used for economic and environmental assessment have been collected from secondary data sources. For AD, the mass and energy data have been collected from the published studies by Achinas et al. (2017), Banks et al. (2011) and Saur and Milbrandt (2014), while the economic data such as the capital costs have been collected from Redman (2010). For gasification, the studies by Hu et al. (2015) and Young (2010) have been adopted to estimate the mass and energy balances while the data from Yassin et al. (2009) has been used for

estimating the capital cost. The cost of electricity, FiT and gate fees have been obtained from BEIS, Ofgem and WRAP, respectively. The prices of products such as hydrogen and methane have been collected from ITM and CNG Europe, respectively. For environmental assessment, GHG conversion factor has been obtained from BEIS.

## 4. Application of STARR framework to a case study of resource recovery and valorisation of waste in the UK

### 4.1. Multilevel system analysis

#### 4.1.1. National level (the UK)

In the UK, a total of 10 million t/y of post-farm gate food waste is generated, primarily contributed by households (71%; 7.3 million t/y), manufacturing (17%; 1.7 million t/y), hospitality and food service (9%; 0.9 million t/y) and retail and wholesale (2%; 0.2 million t/y) (WRAP, 2017a). A material flow diagram showing the generation, distribution, treatment and disposal of food waste in the UK is illustrated in Fig. 3(a). The source analysis (left side of the diagram) has shown that there is a great opportunity of utilising the food waste from households (i.e. since it is the main source of food waste generation). Apart from the food surplus which is considered safe for consumption (0.30 million t/y), the fraction of food waste which is currently sent for recycling through AD or composting (1.80 million t/y), recovery through incineration (3.80 million t/y) and disposal to landfill (4.25 million t/y) can potentially be recovered and valorised, according to the sink analysis (right side of the diagram). Therefore, the fraction for potential resource recovery and valorisation is 9.85 million t/y for the whole UK. It should be noted that the waste arising from the consumption of drinks has been included in the household food waste data but not in the other sectors, due to the nature of the data collection and reporting by WRAP (WRAP, 2017a).

#### 4.1.2. Community level (Households)

The main source of food waste generation in the UK are households (see Fig. 3(a)). A material flow analysis of household food waste management is illustrated in Fig. 3(b). WRAP categorises food waste generated from households into avoidable, possibly avoidable and unavoidable fractions. Based on the source analysis (left side of the diagram), it has been estimated that 4.4 million t/y (60%) of food waste from households are avoidable, followed by possibly avoidable fraction of 1.3 million t/y (18%) and unavoidable fraction of 1.6 million t/y (22%).

Based on the sink analysis (right side of the diagram), food (and

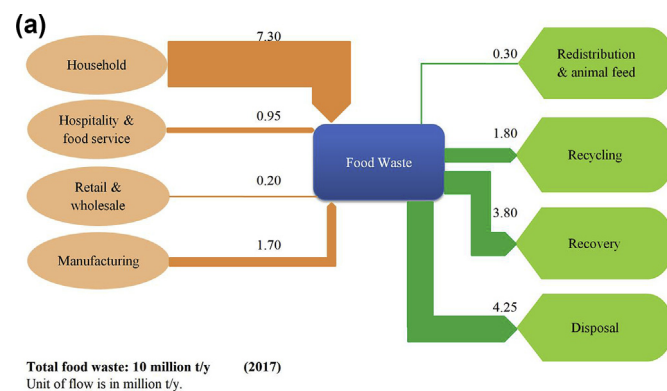
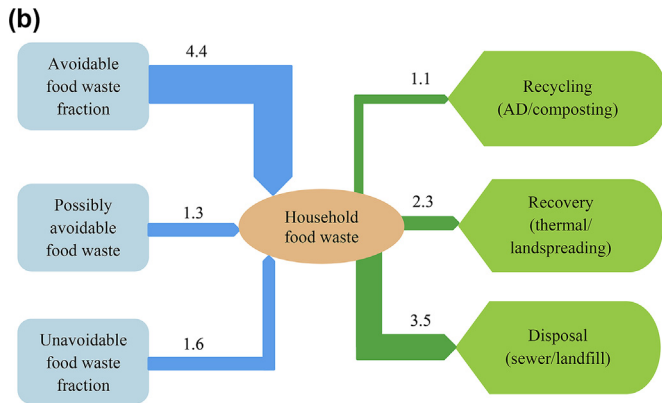


Fig. 3(a). Material flow analysis of food waste generation from the UK post-farm gate sectors and distribution. All flows are reported in million t/y, valid in year 2017. Data is obtained from WRAP (2017a).



Total food waste: 7.3 million t/y

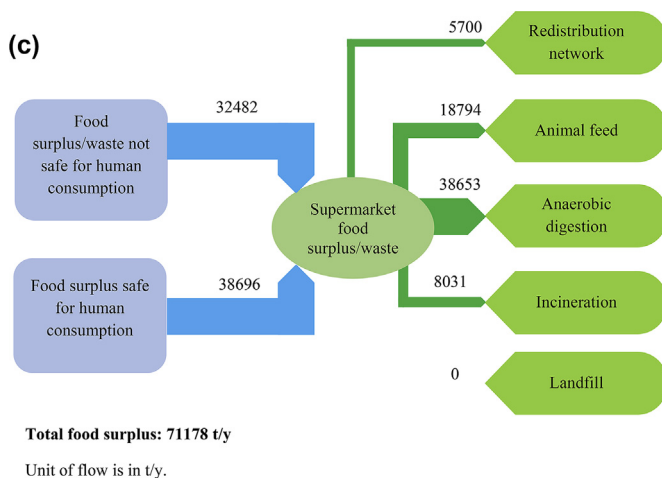
Unit of flow is in million t/y.

**Fig. 3(b).** Material flow analysis of household food waste distribution. All flows are reported in million t/y, valid in year 2016/17. Data is obtained from WRAP (2017a).

drink) waste from households is mostly discharged to sewer or landfill (3.5 million t/y; 50% of total), followed by recovery through incineration and landspreading (2.3 million t/y; 34% of total) and recycling through AD and composting (1.1 million t/y; 16% of total). A total amount of food waste of 7.3 million t/y from all households in the UK can be considered as potential feedstock for recovery and valorisation. This is equivalent to 2683.8 t/y of food waste generated in one community, assuming that there are 27.2 million households in the UK (Office for National Statistics, 2017) and a community size consisting of 10,000 households.

#### 4.1.3. Organisational level (Supermarket)

Based on the source analysis (left side of the diagram) in Fig. 3(c), the food surplus of 38,696 t/y are considered safe for human consumption while 32,482 t/y are not safe for human consumption. The food surplus safe for human consumption is donated to charities through redistribution network (5700 t/y; 8%) and animal feed (18,794 t/y; 26.4%). The food surplus which is not safe for human consumption of 46,684 t/y is sent to AD (38,653 t/y; 54.3%) and incineration (8031 t/y; 11.3%). It has been claimed that no food



Total food surplus: 71178 t/y

Unit of flow is in t/y.

**Fig. 3(c).** Material flow analysis of supermarket food surplus/waste distribution. All flows are reported in t/y, valid in year 2016/17. Data is obtained from Tesco Annual Report 2017 (Tesco, 2017).

surplus is sent directly to the landfill from the supermarket (Tesco, 2017). Based on the sink analysis (right side of the diagram), the food surplus distribution in Fig. 3(c) implies that the food surplus from Tesco (all stores in the UK) available for resource recovery and valorisation is 46,684 t/y (those sent to AD and incineration), where this has considered only the food surplus which is not safe for human consumption. This fraction accounts for 65.6% of the total food surplus generated from Tesco.

## 4.2. Scenario creation

Circular economy and design for sustainability concepts have been incorporated in the design of the waste management and valorisation system by considering the aspects of configuration and technology.

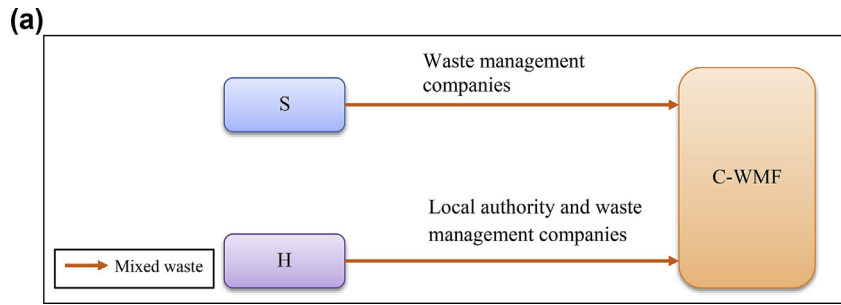
### 4.2.1. Configuration

Fig. 4(a) illustrates the base case where mixed waste is collected and delivered to a centralised waste management facility. The base case represents a linear model (without resource recovery and valorisation) where (i) fossil fuel based electricity from the national grid is supplied to the supermarket and households; (ii) no separate food waste collection; and (iii) no value-added product generation. In this study, decentralised waste management strategies with circular economy model (with resource recovery and valorisation) have been proposed where the food waste valorisation facility is co-located with a supermarket (i.e. without incurring any transportation cost of waste), and the value-added product generated is used locally by the supermarket or households.

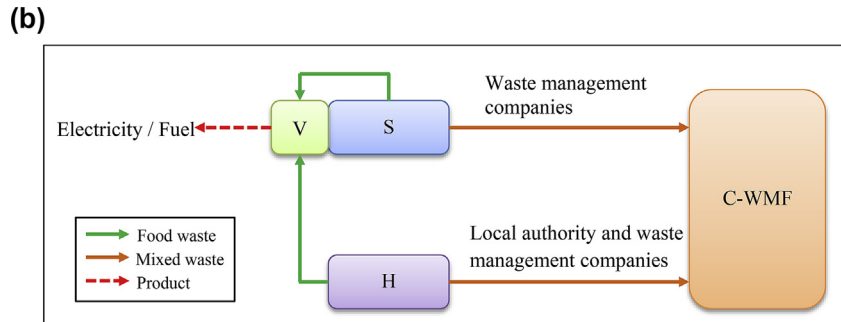
A partially decentralised waste management strategy, Alternative Strategy 1 (AS1) (see Fig. 4(b)) has been proposed where source-segregated food wastes from the supermarket and households are sent to the supermarket-based valorisation facility (collection and transportation of food waste are managed by either household residents or supermarket), while mixed wastes are collected and sent to the centralised waste management facility which is managed by waste management companies and local authorities. Alternative Strategy 2 (AS2), shown in Fig. 4(c) is a completely decentralised waste management strategy where mixed wastes from the supermarket and households are sent to the supermarket-based valorisation facilities, while centralised waste management facility can be eliminated. Collection and transportation of mixed waste from households can be managed by residents, supermarket or local authority. The food or mixed waste valorisation facility generates energy and transportation fuels which can be supplied to the supermarket and/or local community.

### 4.2.2. Technology

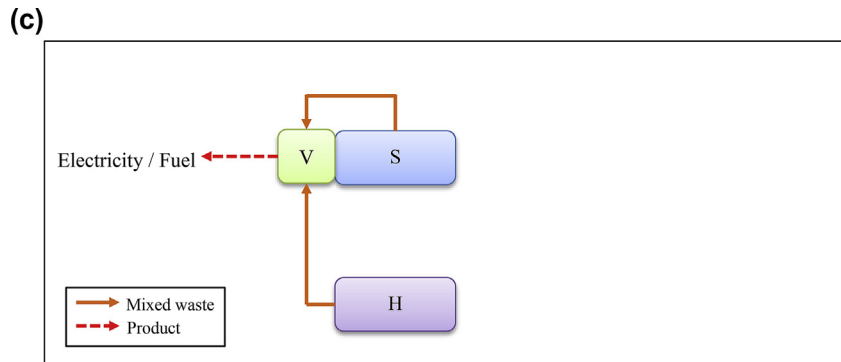
The present study has considered food waste AD and mixed waste gasification technologies. AD generates biogas which mainly consists of methane and carbon dioxide. The biogas is suitable to be used for power generation and can also be upgraded to transportation fuels (i.e. biomethane). Apart from biogas, AD also produces digestate which can be used as fertiliser. AD has been selected because this food waste treatment technology is widely adopted in the UK and is currently supported by the UK government (Priestley, 2016; House of Commons, 2017). On the other hand, gasification has been chosen to be the technology to handle mixed waste because it is flexible in terms of feedstock utilisation and product generation (Ng et al., 2017). Gasification is a technology that converts carbonaceous materials into syngas at high temperature. The syngas mainly consists of carbon monoxide and hydrogen which can further be upgraded into electricity, fuels and chemicals (Ng et al., 2013; Sadhukhan et al., 2014).



**Fig. 4(a).** : Centralised mixed waste management strategy – Base case (S: Supermarket; H: Households; C-WMF: Centralised waste management facility).



**Fig. 4(b).** Partially decentralised food and mixed waste management strategy – AS1 (S: Supermarket; H: Households; C-WMF: Centralised waste management facility; V: Decentralised valorisation facility).



**Fig. 4(c).** Completely decentralised mixed waste management strategy – AS2 (S: Supermarket; H: Households; V: Decentralised valorisation facility).

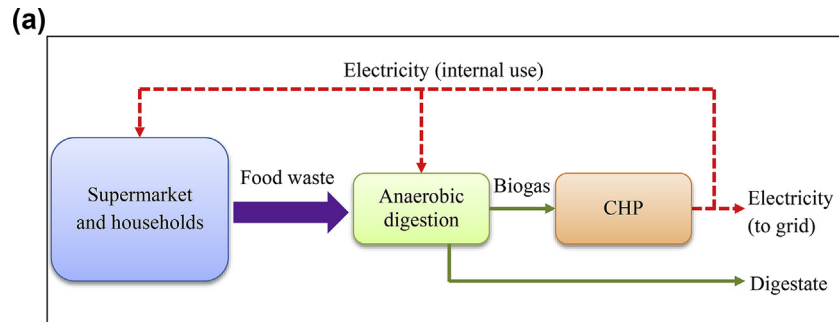
#### 4.2.3. Scenarios

Based on the proposed waste management configurations and technologies, the following three scenarios have been generated for detailed analysis:

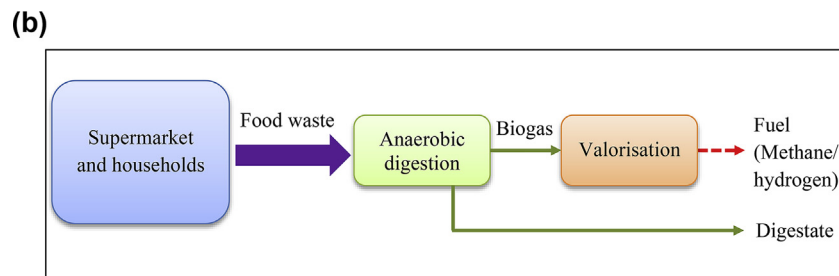
- Scenario 1 (Fig. 5(a)): Partially decentralised food waste management (AS1) through AD and biogas CHP for electricity generation. This scenario considers the current widely promoted AD technology with energy recovery in the UK. AD-E, FW denotes anaerobic digestion of food waste for electricity generation.
- Scenario 2 (Fig. 5(b)): Partially decentralised food waste management (AS1) through AD and valorisation of biogas for fuel (methane or hydrogen) production. This scenario presents the modified AD technology for fuel production which has the potential of becoming the next generation of waste valorisation technology. AD-CH<sub>4</sub>, FW and AD-H<sub>2</sub>, FW denote anaerobic digestion of food waste for methane and hydrogen production, respectively.

- Scenario 3 (Fig. 5(c)): Completely decentralised mixed waste management (AS2) through gasification and valorisation of syngas for electricity or fuel (hydrogen) production. This scenario offers a futuristic case where a more flexible and advanced technological platform has been used. GAS-E, MW and GAS-H<sub>2</sub>, MW denote gasification of mixed waste for methane and hydrogen production, respectively.

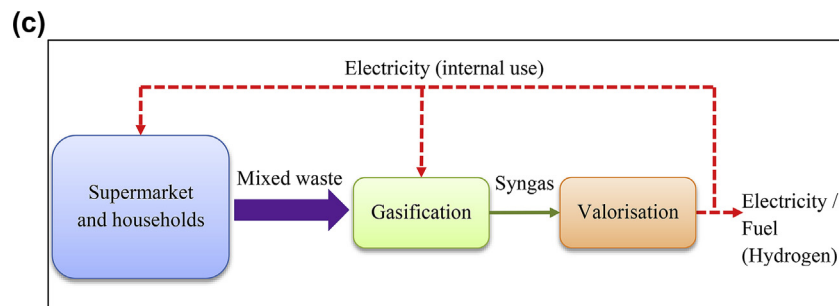
Scenario 1 (Fig. 5(a)) presents a partially decentralised waste management strategy (AS1) where source-segregated food waste is treated and valorised in an on-site waste management facility at the supermarket while mixed waste is sent to the centralised waste management facility. The AD facility generates biogas which is subsequently converted into electricity through CHP. The electricity is used to meet the internal electricity demand in AD and also part of the electricity demand of the supermarket or households. AD also produces digestate which can be used as fertiliser for local agriculture. It has been assumed that the heat generated is used



**Fig. 5(a).** Scenario 1 – AS1 with AD-E, FW. Partially decentralised food waste management through AD and biogas CHP for electricity generation. AD facility is located on-site at the supermarket.



**Fig. 5(b).** Scenario 2 – AS1 with AD-CH<sub>4</sub>/H<sub>2</sub>, FW. Partially decentralised food waste management through AD and valorisation of biogas for fuel (methane or hydrogen) production. AD facility is located on-site at the supermarket.



**Fig. 5(c).** Scenario 3 – AS2 with GAS-E/H<sub>2</sub>, MW. Completely decentralised mixed waste management through gasification and valorisation of syngas for electricity or fuel (hydrogen) production. Gasification facility is located on-site at the supermarket.

internally to maintain the temperature of AD and thus no heat is exported. Sainsbury's supermarket has utilised the energy converted from own food waste through AD managed by ReFood to supply some of the store's energy demand (Sainsbury's, 2016). This shows that there is a strong motivation from supermarket viewpoint in driving such initiative in using renewable energy from food waste.

Similar to Scenario 1, Scenario 2 (Fig. 5(b)) also presents a partially decentralised waste management strategy (AS1), however with particular focus on the production of transportation fuel instead of electricity. This is an emerging scenario where a more advanced AD facility is installed with biogas valorisation into fuels or green gases such as methane and hydrogen. The transportation fuels can be used in either compressed natural gas (CNG) vehicles or hydrogen fuel cell electric vehicles, as alternatives to fossil fuels (e.g. petrol, diesel). To obtain methane, biogas undergoes a series of upgrading processes to remove trace contaminants and calorific value adjustment to meet the vehicle fuel standards (Ryckebosch et al., 2011). On the other hand, hydrogen can be obtained from

biogas through steam methane reforming process (Saur and Milbrandt, 2014). CNG is an alternative fuel to diesel and the application of CNG in vehicles is expected to increase due to the UK government proposal in banning diesel and petrol cars by 2040. Waitrose supermarket has launched the use of biomethane in their modified Scania trucks, in partnership with biomethane supplier CNG Fuels (CNG Fuels, 2017). With regard to hydrogen fuel, the potential and popularity of hydrogen fuel cell cars (e.g. Toyota Mirai and Hyundai ix35) in the UK is uncertain mainly due to the lack of refuelling stations around the country. This strategy of using green gases as transportation fuels aligns with *The UK's Clean Growth Strategy* and it is highly likely to be adopted in the near future.

Scenario 3 (Fig. 5(c)) presents a completely decentralised waste management facility using gasification technology located adjacent to a supermarket. Gasification is a flexible technology where it can utilise mixed waste as feedstock and thus upstream segregation of food waste at source is not needed. Gasification transforms mixed waste into syngas, a valuable intermediate product which can be subsequently converted into electricity and hydrogen. Scenario 3



**Table 1**  
Basis for food and mixed waste generation from supermarket and households.

Specification	Value	
<i>General assumption</i>		
Total number of households in the UK	27.2 million (Office for National Statistics, 2017)	
Number of households in one community	10,000	
Households	Food Waste	Mixed Waste
Total amount of waste from households in the UK per year	7.3 million t/y (WRAP, 2017a)	27.3 million t/y (DEFRA, 2018)
Amount of waste generated per household per year	0.268 t/y	1.004 t/y
Amount of waste generated in one community per year	2683.8 t/y	10,039.0 t/y
<i>Supermarket</i>		
Amount of waste generated per store	85.2 t/y <sup>(i)</sup>	10,039.0 t/y <sup>(ii)</sup>

Note:

<sup>(i)</sup> It has been assumed that the food waste is generated from a store equivalent size to a Tesco Extra store. Only food waste that is not safe for consumption has been accounted. The amount of food waste generated per store has been deduced from the average space per store and average food sales per store. Details can be found in the Supplementary Data: Part A.

<sup>(ii)</sup> The data for mixed waste from the supermarket is confidential. It has been assumed that the amount of mixed waste generated from a supermarket is equivalent to the amount of mixed waste generated from households in one community.

has also been examined for the case where food waste fraction is completely separated from mixed waste, i.e. GAS-E, FW and GAS-H2, FW.

#### 4.3. Sustainability assessment

The three scenarios laid out in Section 4.2.3 have been evaluated with respect to economic, environment and social dimensions of sustainability with the objectives of presenting a pertinent and viable case to the government, policy makers and investors. (Note: The objective of this study is to present alternative strategies rather than selecting the best performing scenario).

##### Basis:

In this study, it has been assumed that only source-segregated food waste is used in AD for Scenarios 1 and 2 while mixed waste is used in gasification for Scenario 3. The amount of waste available for valorisation has been taken to be 2769 t/y of source-segregated food waste (2683.8 t/y from households + 85.2 t/y from supermarket) for both Scenarios 1 and 2, and 20,078 t/y of mixed waste (10,039 t/y from households + 10,039 t/y from supermarket) for Scenario 3. It can be assumed that mixed waste consists of 18% of food waste (DEFRA, 2008) and if all food waste fraction from the mixed waste in Scenario 3 is extracted, 3614 t/y of food waste can be obtained.

Only food waste (not drink waste) is considered in the analysis, unless otherwise stated. Relatively large supermarkets have been considered in this study, assuming that one supermarket can serve an average community size of 10,000 households. A supermarket of such a size is equivalent to a Tesco Extra store in the UK (i.e. average store space of 6543 m<sup>2</sup> (Tesco, 2017)), which in most cases includes a fuelling station, waste collection and recycling bins, and has sufficient space to build a small to moderate scale waste processing facility adjacent to it.

Table 1 summarises the basis for food and mixed waste generated from the supermarket and households.

##### 4.3.1. Economic case

The indicative capital and operating costs of the waste valorisation facilities, i.e. AD and gasification, in each scenario have been evaluated, shown in Table 2, based on 2769 t/y of food waste for Scenarios 1 and 2, and 20,078 t/y of mixed waste for Scenario 3. The results indicate that the orders of capital and operating costs of the technologies, from the highest to lowest, are Scenario 3 > Scenario 2 > Scenario 1.

For a supermarket with store space equivalent to a Tesco Extra store (i.e. average store space of 6543 m<sup>2</sup>), the annual electricity

consumption has been estimated to be 3696.8 MWh/y, assuming an annual electricity consumption per unit store space of 565 kWh/m<sup>2</sup> (Spyrou et al., 2011; Tesco, 2017). This corresponds to 0.48 million £/y for the cost of electricity for one supermarket, assuming unit electricity price of 12.88 p/kWh (BEIS, 2017a). Fig. 6(a) shows a comparison of cost of electricity for a supermarket with and without on-site electricity generation from waste. It has been estimated that AD and gasification generate net electricity outputs of 156.4 kWh/t of food waste and 685 kWh/t of mixed waste, respectively (Young, 2010; Banks et al., 2011) (See Supplementary Data: Part B for the calculation). This suggests that 432.9 MWh/y of net electricity output is generated from 2769 t/y of source-

**Table 2**  
Indicative capital and operating costs of AD and gasification plants in each scenario.

Specification	Unit	Scenario 1	Scenario 2	Scenario 3
		AD-E	AD-CH4/H2	GAS-E/H2
Capital cost	£/t	102.5 <sup>(i)</sup>	361.8 <sup>(ii)</sup>	621.1 <sup>(iii)</sup>
	million £	0.284	1.002	12.47 (2.24) <sup>(iv)</sup>
Operating cost	£/t	4.3 <sup>(i)</sup>	32.1 <sup>(ii)</sup>	60.0 <sup>(iii)</sup>
	million £/y	0.0119	0.089	1.205 (0.217) <sup>(iv)</sup>

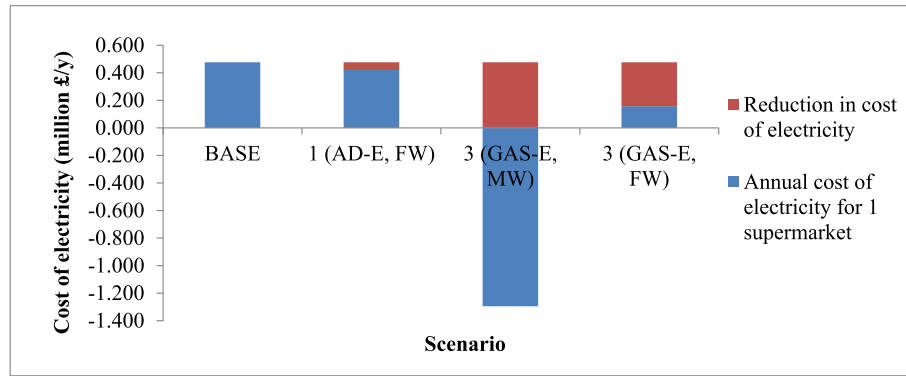
Note:

<sup>(i)</sup> The capital cost of AD is given at 4000 £/kW (Redman, 2010). The electricity generation capacity for AD in the present case is 224.6 kWh/t of food waste which is equivalent to 0.0256 kW/t of food waste, assuming 8760 operating hours per year. Hence, the capital cost is 4000 £/kW × 0.0256 kW/t = 102.5 £/t of food waste. It has been assumed that the operating cost of AD is contributed predominantly by its maintenance cost. The maintenance cost of AD is estimated based on 2% of the total capital cost while the maintenance cost of CHP is 0.01 £/kWh of electricity generation. Hence, the maintenance cost = (0.02 × 102.5£/t) + (0.01 £/kWh × 224.6 kWh/t of food waste) = 4.3 £/t.

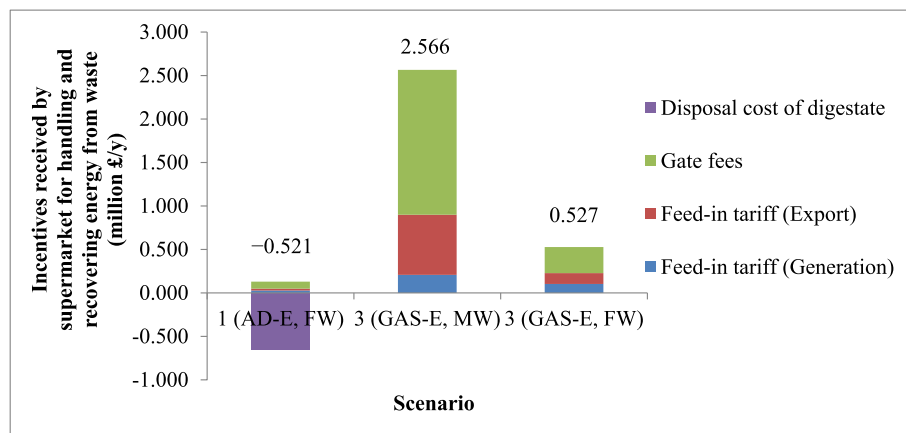
<sup>(ii)</sup> Due to the lack of published information on the advanced AD with biomethane and hydrogen production facilities, the corresponding indicative capital and operating costs have been assumed to be the average costs of AD with CHP and gasification facilities. The costs assumed to be the same regardless of the product generated.

<sup>(iii)</sup> Yassin et al. (2009) provides cost estimation for 50 kt/y and 100 kt/y gasification facility, which are 28.8 million and 45 million £ (2007), respectively. The costs have been converted to £ (1 £ = 1.4 € in 2007) and levelised to year 2017, i.e. 22.4 and 35.1 million £ for 50 kt/y and 100 kt/y gasification facility, respectively, using Chemical Engineering Plant Cost Index (CEPCI) of 525.4 (2007) and 573.1 (2017). Based on the cost and size information, a scale factor,  $R$  of 0.64 has been derived using the equation  $(\text{Cost } 2/\text{Cost } 1) = (\text{Size } 2/\text{Size } 1)^R$ . In the present case, the gasification facility has a scale of 20 kt/y and hence the corresponding cost has been estimated to be 12.47 million £ or 621.1 £/t. The operating cost is adopted from Yassin et al. (2009). The costs assumed to be the same regardless of the product generated.

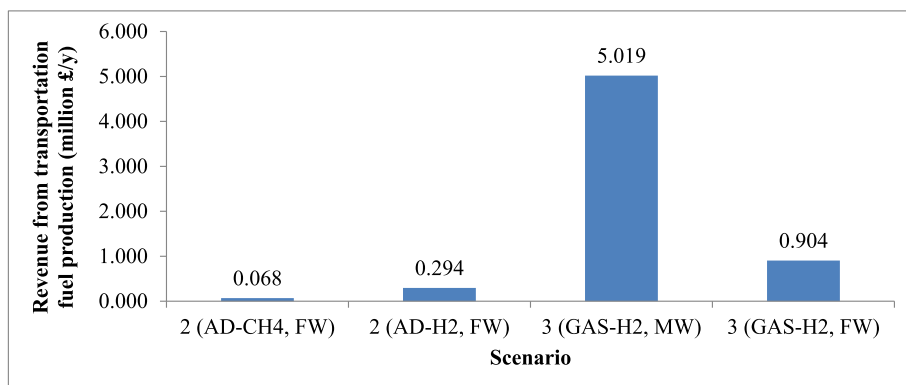
<sup>(iv)</sup> The values in parenthesis represent the capital or operating cost of the system if only food waste is used as the input instead of mixed waste. It has been assumed that the food waste fraction (18%) is extracted from the mixed waste (DEFRA, 2008).



(a)



(b)



(c)

**Fig. 6.** Economic cost-benefit analysis of integrated supermarket and waste valorisation facility scenarios. (a) annual cost of electricity for supermarket; (b) incentives received by supermarket for handling and recovering energy from waste; (c) revenue from transportation fuel production.

segregated food waste in Scenario 1, and 13,753.4 MWh/y of net electricity output is generated from 20,078 t/y of mixed waste in Scenario 3, which is then supplied to the supermarket, respectively. This configuration in Scenario 1 has reduced the supermarket's electricity dependency on the grid and hence the cost of electricity of supermarket has been reduced by 11.7%. In Scenario 3, the electricity generated from mixed waste is able to meet the requirement of the supermarket (i.e. resulting in zero annual cost of electricity or 0.48 million £/y of cost savings), while creating 10,056.6 MWh/y of net surplus electricity which can be exported to

the national grid (i.e. creating a revenue of 1.3 million £/y). If the food waste fraction (3614 t/y) is extracted from the mixed waste in Scenario 3 (GAS-E, FW) and recovered to generate electricity, this can reduce the fossil fuel based electricity from the grid by 67% (Note: It has been assumed that same net electricity output per unit of feedstock of 685 kWh/t can be achieved from gasification of either food waste or mixed waste. It should be reminded that the net electricity generation is highly dependent on the waste characteristic and composition. Due to lack of published data, the estimated benefit may be optimistic.)

In principle, if the waste valorisation facility is owned by the supermarket and it handles the waste collected from households, then the supermarket will be entitled to receiving gate fees paid by the local authority. The local authority pays the gate fees at different rates depending on the treatment technologies. Currently, AD facility received 29 £/t of waste treated, while Energy-from-Waste (EfW) facility generally received 83 £/t (Note: These are median values reported by WRAP (2017b)). The gate fee for gasification in this study has been assumed to be the same as EfW. RHI is not applicable in the present context where biomethane is used as transportation fuel since it is only eligible if biomethane is injected into the grid or biogas is used directly for heat generation (Ofgem, 2018a). The present analysis has also assumed that only electricity generated (i.e. excluding heat) from AD is supplied to the supermarket. The impacts and benefits attributed to gate fees, FiT and disposal cost of digestate have been analysed for Scenarios 1 and 3, illustrated in Fig. 6(b).

The gate fees received in Scenarios 1 (AD-E, FW) and 3 (GAS-E, MW) have been found to be 0.08 million £/y and 1.7 million £/y for handling 2769 t/y of food waste and 20,078 t/y of mixed waste, respectively. The installed capacity of AD is 71 kW (electricity generation capacity of 224.6 kWh/t of food waste) and has a FiT generation rate of 0.044 £/kWh (Ofgem, 2018b). The export tariff is independent of the installed capacity and has a standard rate of 0.05 £/kWh (Ofgem, 2018b). This has resulted in a total of 0.049 million £/y of FiT (0.027 million £/y of generation tariff and 0.022 million £/y of export tariff) received by the AD facility owned by the supermarket in Scenario 1.

The overall incentives received by the supermarket in Scenario 1, however, will be counteracted by the disposal cost of 0.651 million £/y to deal with 174.4 kt of digestate (the yield of digestate has been estimated to be 63 t/t of food waste (Banks et al., 2011) and the disposal cost of digestate has been assumed to be £3.73 per tonne (WRAP, 2013b)). This has given rise to negative benefit on Scenarios 1.

FiT is not applicable in Scenario 3 in the present context since the installed capacity of the gasification facility is 1570 kW (i.e. only CHP unit which generates less than 2 kW of electricity is eligible for FiT under the current UK policy (Ofgem, 2016)). However, a hypothetical case has been presented for Scenario 3 and it has provided some insights if FiT (same rate as AD) is considered for large scale gasification. Therefore, a total FiT of 0.9 million £/y (0.2 million £/y of generation tariff and 0.7 million £/y of export tariff) is received by the gasification facility owned by the supermarket in Scenario 3, using a FiT generation rate of 0.151 £/kWh (for installed capacity >500 kW) and export rate of 0.05 £/kWh.

If the food waste fraction (18%; 3614 t/y) is extracted from the mixed waste in Scenario 3 (GAS-E, FW) and recovered for electricity generation, the facility can receive FiT of 0.23 million £/y (0.1 million £/y of generation tariff and 0.13 million £/y of export tariff) and gate fee of 0.3 million £/y. The gate fees received by EfW is 3 times higher compared to AD. As shown in Fig. 6(b), there is a strong motivation to increase the FiT and gate fees for AD in order to be able to compete with EfW technologies and to recover the cost of digestate disposal. Unfortunately, the AD at its current scale is not eligible for CfD since it is lower than 5 MW generating capacity, and similarly for gasification. A more supportive scheme for incentivising AD, e.g. by lowering the threshold of generating capacity of 5 MW in CfD (as most AD plants are operated at smaller scale), is needed in the UK to support the community-based waste management projects.

Fig. 6(c) illustrates the potential revenue that can be generated from valorising waste into transportation fuels. The revenue generated from hydrogen production is 4 times higher compared to methane production despite the yield of methane (0.0351 t/t of

food waste) is 3 times higher than hydrogen (0.0106 t/t of food waste) (see Supplementary Data: Part B). This is mainly attributed to the considerable higher market price of hydrogen (10 £/kg (ITM Power, 2017)) compared to methane (0.7 £/kg (CNG Europe, 2017)). The production of hydrogen using gasification technology in Scenario 3 is higher and thus is more promising compared to AD in Scenario 2.

If the electricity generated from AD or gasification is used to supply the households' electricity demand instead of the supermarket, the households can be benefited from renewable electricity supplied from supermarket-based AD (Scenario 1) or gasification (Scenario 3) with up to a maximum savings of 5.6–177.1 £/y on electricity bills per household, presented in Table 3. In this case, Scenario 3 is more compelling compared to Scenario 1 in terms of the cost saving per household.

In the base case, two trucks (refuse collection vehicles) with daily collection of waste from the supermarket and households to the centralised waste management facility have been assumed. The transportation cost of waste generally increases with the distance from the source of waste to the waste valorisation facility (Ng and Sathukhan, 2011a, 2011b). The cost of fuel (diesel) has been estimated to be 8135.4 £/y for 2 trucks (i.e. 4067.7 £/y per truck) to transport 10,039 t/y of mixed waste over a total distance of 14,600 miles/y (round trips for 2 trucks, i.e. 7300 miles/y per truck) from the source of waste to the centralised facility, shown in Table 4. The cost of a truck is 130,000 £ (Leeds City Council, 2012).

#### 4.3.2. Environmental case

Table 5(a) presents the GHG emissions associated with electricity consumption in one supermarket store and the potential GHG saving if renewable electricity from waste is utilised within the supermarket. Scenario 1 has shown 152.2 t CO<sub>2</sub>-eq/y of GHG emissions can be avoided (i.e. 11.7% GHG savings compared to the base case) while Scenario 3 with net surplus of electricity generated has resulted in greater GHG emissions avoidance of 4835.1 t CO<sub>2</sub>-eq/y (i.e. 1299.7 t CO<sub>2</sub>-eq/y of GHG emissions associated with electricity consumption in the store can be avoided). This is attributed to 4.4 times more electricity generated per unit feedstock from mixed waste gasification than food waste AD (See Supplementary Data: Part B for the calculation) and thereby achieving greater substitution for fossil fuel based electricity from the grid. In the case where only the food waste fraction in mixed waste is considered in Scenario 3, 67% of GHG savings can be achieved. On the other hand, if the renewable electricity from waste is supplied to the households, Scenario 3 achieves 44.4% GHG savings (8% if food waste fraction is extracted from mixed waste) compared to Scenario 1 with 1.4% GHG savings, as demonstrated in Table 5(b).

With respect to GHG emission savings associated with displacement of transportation fuel for heavy goods vehicles (HGV) by renewable fuel, it has been estimated that a maximum of 128.3 t CO<sub>2</sub>-eq/y of GHG emissions can be avoided per HGV truck with annual fuel consumption of 40,208.3 kg/y (assuming annual distance of 187,500 km/y and average fuel consumption of vehicle of 0.214 kg/km (Cluzel et al., 2017)) if diesel fuelled HGV is fully substituted with renewable fuels such as methane and hydrogen. A GHG conversion factor of 3190.3 kg CO<sub>2</sub>-eq/t of diesel has been adopted in the estimation (BEIS, 2017c).

The collection and transportation of waste from the source of waste (supermarket/households) involves GHG emissions of 8865 kg CO<sub>2</sub>-eq/y for a truck (refuse collection vehicle) due to the use of diesel. The amount of diesel use per truck has been estimated to be 3317.85 L/y using the basis given in Table 4. A GHG conversion factor of 2.672 kg CO<sub>2</sub>-eq/L of diesel has been adopted in the estimation (BEIS, 2017c). If a centralised facility can be replaced by a

**Table 3**  
Benefit for households from renewable electricity generation.

Specification	Unit	Base Case	Scenario 1	Scenario 3
		Electricity from grid (i)	AD-E	GAS-E
Renewable electricity generated from waste valorisation facility and supplied to community <sup>(iii)</sup> / households	MWh/ y	0	432.9	13,753.4 (2475.6) <sup>(iv)</sup>
Annual fossil fuel based electricity supplied from the grid for 1 community	MWh/ y	31,000 <sup>(iii)</sup>	30,567.1	17,246.6 (28,524.4) <sup>(iv)</sup>
Annual fossil fuel based electricity supplied from the grid for 1 household	MWh/ y	3.1	3.06	1.72 (2.85) <sup>(iv)</sup>
Annual cost of electricity for 1 household	£/y	399.3	399.3	399.3
Annual cost of electricity for 1 household considering the fraction of fossil fuel based electricity supply	£/y	399.3	393.7	222.1 (367.4) <sup>(iv)</sup>
Maximum potential reduction in cost of electricity attributed to the supply of renewable electricity	£/y	0.0	5.6	177.1 (31.9) <sup>(iv)</sup>

Note:

(i) Electricity from the grid has been assumed to be 100% sourced from fossil fuel.

(ii) 1 community is assumed to comprise 10,000 households.

(iii) The typical domestic consumption value (TDCV) per household in the UK is 3100 kWh/y (BEIS, 2017b).

(iv) The values in parenthesis represent the results if only food waste is used as the input instead of mixed waste. It has been assumed that the food waste fraction (18%) is extracted from the mixed waste (DEFRA, 2008).

**Table 4**  
Estimation of fuel consumption and costs for waste transportation from source of waste (households/supermarket) to the centralised waste management facility.

Parameter	Value	Unit
Truck loading capacity	26 <sup>a</sup>	t/truck
Average waste to be transported per day	27.5 <sup>b</sup>	t/d
Number of rounds of transporting per day	1 <sup>c</sup>	rounds/d
Amount of waste transported per truck per day	26 <sup>d</sup>	t/truck-d
Number of trucks needed	2 <sup>e</sup>	Truck
Distance (single trip)	10 <sup>f</sup>	miles/single-trip
Distance (round trip)	20 <sup>g</sup>	miles/round-trip
Total distance travelled per truck per day	20	miles/d
Total distance travelled for all trucks per day	40	miles/d
Total distance travelled for all trucks per year	14,600 <sup>h</sup>	miles/y
Fuel consumption	0.4545 <sup>i</sup>	L/miles
Total fuel use	6635.7	L/y
Unit cost of fuel	1.226 <sup>j</sup>	£/L
<b>Total cost of fuel per year</b>	<b>8135.4</b>	<b>£/y</b>

Note:

<sup>a</sup> The loading capacity is equivalent to a Mercedes Atego truck (WRAP, 2010).

<sup>b</sup> This has been estimated by dividing the total waste to be transported by 365 days a year (i.e. waste is collected on a daily basis).

<sup>c</sup> This is an assumption.

<sup>d</sup> This has been estimated by truck loading capacity × Number of rounds of transporting per day.

<sup>e</sup> This has been estimated by average waste to be transported per day ÷ amount of waste transported per truck per day, and round up to the nearest integer.

<sup>f</sup> The centralised waste management facility is assumed to be located 10 miles away from the source of waste.

<sup>g</sup> The truck travels the same distance to and from the source of waste to the centralised waste management facility.

<sup>h</sup> The truck runs 365 days per year.

<sup>i</sup> Fuel consumption is reported at 10 mpg (1 mpg = 2.2 miles/L) (WRAP, 2010).

<sup>j</sup> Diesel price valid in March 2018 (AA, 2018).

decentralised facility or diesel can be replaced by renewable fuel from waste, 8865 kg CO<sub>2</sub>-eq/y of GHG emissions from a refuse collection vehicle can be avoided.

#### 4.3.3. Social case

Public intervention can occur at waste separation and collection stages as well as planning and operational phases of the waste management infrastructure (Chang and Pires, 2015; Iacovidou et al., 2017b). In the present context, the following social aspects have been assessed.

**Social function and equity and level of involvement** – This is associated with the convenience and monetary benefits and impacts in relation to the local residents resulting from the

implementation of decentralised waste valorisation at the supermarket. The proposed decentralised strategies involve partial and complete disconnection of waste collection services provided by the local authority. This suggests that either residents or supermarket may need to take up the responsibility of transporting waste from households to the supermarket. Such community-based approach would enhance residents' awareness and level of participation in waste management.

**Health and safety** – The implementation of waste management facility at the supermarket such as AD and gasification must conform to the regulations imposed by the *Environmental Permitting (England and Wales) Regulations 2010*, *Industrial Emissions Directive 2010/75/EU*, *Animal By-Product Regulations* (particularly for AD) and *Duty of Care* (Ashurst, 2016; The Official Information Portal on Anaerobic Digestion, 2018). Risk assessment has to be conducted based on the regulations set out by the UK Health and Safety Executive (HSE).

**Job creation** – Investing new resource recovery from waste infrastructure promotes job creation in green industry. The job creation potential is dependent on the capacity, sophistication and level of automation of the waste management facility (SITA UK, 2012). Based on these factors, Scenarios 1 and 2 with smaller scale decentralised AD facility is expected to involve less number of workers compared to a larger scale gasification facility in Scenario 3. SITA has estimated that approximately 4000–6000 of direct jobs and 6000–8000 of indirect jobs can potentially be created if new infrastructure is invested in the organic treatment and EfW sectors throughout the UK (SITA UK, 2012).

## 5. Conclusions

This paper has presented a systematic STARR framework for sustainable resource recovery and valorisation strategies, which has incorporated the circular economy, industrial ecology and design for sustainability principles. The challenges and opportunities of adopting an integrated and collaborative approach in waste management has been explored with the aim of enhancing interaction among the commercial, domestic and waste management sectors. Decentralised waste processing strategies using AD and gasification in unlocking the full potential of resource recovery from waste have been investigated. In particular, this study has examined in detail the potential of utilising source-segregated food waste as well as mixed waste from the domestic (i.e. households) and commercial (i.e. supermarket) sectors in an on-site waste



**Table 5**

Avoided GHG emissions from (a) supermarket; (b) households attributed to utilisation of renewable electricity generated from waste as a substitute for fossil fuels.

(a)				
Specification	Unit	Base Case	Scenario 1	Scenario 3
		Electricity from grid <sup>(i)</sup>	AD-E	GAS-E
Annual fossil based electricity demand from the grid for 1 supermarket store	MWh/y	3696.8	3263.9	–10,056.6 (1221.2) <sup>(ii)</sup>
GHG emissions associated with electricity consumption in 1 supermarket store	t CO <sub>2</sub> -eq/y	1299.7	1147.4	–3535.5 (429.3) <sup>(ii)</sup>
Avoided GHG emissions from 1 supermarket store attributed to the utilisation of renewable electricity generated from waste as a substitute for fossil fuels	t CO <sub>2</sub> -eq/y	0	152.2	4835.1 (870.3) <sup>(ii)</sup>
(b)				
Specification	Unit	Base Case	Scenario 1	Scenario 3
		Electricity from grid <sup>(i)</sup>	AD-E	GAS-E
Annual fossil based electricity demand from the grid for 1 household	MWh/y	3.1	3.06	1.72 (2.85) <sup>(ii)</sup>
GHG emissions associated with electricity consumption in 1 household	t CO <sub>2</sub> -eq/y	1.09	1.07	0.61 (1.0) <sup>(ii)</sup>
Avoided GHG emissions from 1 household attributed to the utilisation of renewable electricity generated from waste as a substitute for fossil fuels	t CO <sub>2</sub> -eq/y	0	0.0152	0.484 (0.087) <sup>(ii)</sup>

Note:

<sup>(i)</sup> Electricity from the grid has been assumed to be 100% sourced from fossil fuel.<sup>(ii)</sup> The values in parenthesis represent the results if only food waste is used as the input instead of mixed waste. It has been assumed that the food waste fraction (18%) is extracted from the mixed waste (DEFRA, 2008).

valorisation facility co-located with a supermarket to generate electricity and transportation fuels.

Complementary to the existing literature on food waste management, the present study has contributed to the following. The review of policies has indicated that: (i) the waste management policies in the UK are heavily influenced by the *EU Waste Framework Directive*; (ii) food waste collection and reduction are not standardised throughout the UK; and (iii) energy recovery from waste is the preferred option in the UK. The multilevel system analysis has revealed the availability of food waste that can potentially be used for resource recovery and valorisation at the national level (the UK), community level (households) and organisational level (supermarket). The economic and environmental cost-benefit analyses have shown that the completely decentralised mixed waste gasification strategy can achieve greater electricity cost savings and GHG emission savings compared to the partially decentralised food waste AD strategy, while GHG emissions attributed to the collection and transportation of waste can also be avoided. Decentralised waste management strategies can be adapted accordingly based on the availability of waste feedstock at local community, capacity of waste valorisation facility, distance of waste transportation, value of product generation and fiscal incentives. From the social perspectives, introducing a community-based approach in waste management can create job opportunities at local level and promote higher participation of various stakeholders in the community.

**Theoretical implications:** The findings have shown various economic, environmental and social benefits of undertaking a circular economy approach, with systems thinking at its core, in addressing waste problems. Appropriate strategies for waste management and valorisation enables minimisation of the cost and GHG emission impacts associated with the collection, transportation, processing and disposal of waste. Therefore, the proposed STARR framework has important implications in terms of creating a more sustainable waste management model.

The following recommendations can be considered to create

appropriate strategy and delivery plan to unlock the full potential of resource recovery from waste and promote green growth.

- (i) A collaborative approach can be adopted through redistribution of responsibility among the local authorities, waste management companies and local communities. This offers a wide range of benefits to all parties from a whole system standpoint.
- (ii) Small-scale decentralised waste valorisation facilities are benefited from minimum transportation cost. Nevertheless, it is advisable to investigate the economies of scale and trade-offs of such strategy on a case-by-case basis.
- (iii) Supermarkets should consider publishing a comprehensive and transparent set of food waste as well as adopting a systematic circular and technological approach in addressing food waste problem.
- (iv) It is imperative to introduce a more supportive incentive scheme for AD technology in the UK. More technology success and failure evidences for gasification are needed to formulate a supportive incentive scheme for the technology.

**Practical implications:** This research has important implications to the society in terms of promoting resource recovery and increase diversion of waste from landfill through a collaborative approach. Recovering and valorising food waste at community level enables production of cleaner and affordable energy to the local community. This research has informed decision-making in terms of alternative decentralised waste recovery/valorisation strategy using a circular model that can be considered in the UK as compared to the conventional centralised management strategy using a linear model.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jclepro.2019.04.136>.

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